

Response to interactive comment of Referee #1 on “Experimental total uncertainty of the derived GNSS-integrated water vapour using four co-located techniques in Finland” by E. Fionda et al.

Anonymous Referee #1

Received and published: 18 August 2018

In black => referee observations

In red => our response

General Comments

The manuscript presents a multisensor comparison of the Integrated Water Vapour (IWV) in the atmosphere using GPS, radiosondes, and two ground-based microwave radiometers. The focus is on the GPS, but also calibration of the microwave radiometers and the so called dry bias effect for the radiosondes are mentioned. The work does not (to my knowledge) present any new knowledge in terms of significantly different conclusions compared to previously published comparisons using these types of sensors. I characterise the manuscript as being the basis for a "confirmation paper". The data are unique and - as the authors also state in the manuscript - "it is useful to periodically repeat comparison campaigns between datasets". Having said that I think that the manuscript is well structured and focused on the important issues. My only concern in terms of length of the text is the conclusions.

We greatly appreciate the referee's very constructive and valuable comments. Below we have tried to address all the reviewer's comments (General, Specific Comments and Technical Corrections) and we modified the manuscript accordingly. All comments and technical corrections are included in the current submitted version of the manuscript.

There is no need to repeat many of the results, especially since it is a short paper. My suggestion is to keep the text on page 9 and delete the text on page 10 (some rewriting on page 9 will be necessary because of this). *You may want to modify the text on page 9* in order to specifically mention that *the real differences between the two sites dominate the observed differences* (as least during the wetter part of the year), depending how you handle the suggestions below.

Following the suggestion and agreeing with the comment, we have rewritten part of the text on page 9 and deleted some on page 10. Also, following suggestions of Reviewer #2 we have added some discussion of the instrument's FOVs (fields of view) and added 2 Tables (Tab 2 and 3).

I think there is a potential for improvement of the manuscript and some suggestions are given below. Specifically I think the true variability in the IWV between the GPS site and the site of the other sensors could be taken further, although I cannot predict how interesting the result(s) will be.

We thank the reviewer for the suggestion We added Fig. 3 And Table 2 and added discussion in section 3.1 to discuss specifically this point.

Specific comment:

The abstract is unnecessarily long and includes introductory information. I think you can ignore to mention the name of the experiment as well as how the GPS data were processed. Such information is already, as it should be, in Section 2.

We agree with the reviewer and have shortened the abstract and eliminated the information that is in section 2.

The 20 km distance between the GPS and the other instruments is in several aspects a disadvantage but it does allow to try to separate the true RMS difference between the sites and the instrumental errors. Together these two effects cause the observed differences and it would be more clear if you would refer to the total RMS differences between GPS and the other sensors rather than RMS Error (RMSE).

Following both reviewers' comments we have eliminated the RMSD and kept the mean differences and standard deviation of differences. The results are now referred to as "differences due to the field of view" and "differences due to the distance".

Part of the observed differences between GPS and the other sensors are signals, not errors. I recommend not to use the term representativeness error but rather true differences, or something similar.

We followed the reviewers' suggestion and eliminated the term representativeness error and now we refer to the differences due to the FOV and to the distance in addition to the true random uncertainty of the instruments.

You state that the GPS and MWR data were averaged for 15 minutes around the RAOB launch time. It would make more sense to make the average for a period starting at the launch time because that is the time when the RAOB sampling starts and it needs many minutes to rise through the layers with the main part of the water vapour.

We have been imprecise in writing the sentence on pp. 3 line 12 of the manuscript. The average values were taken over a time interval of 15 minutes from the launch time of radiosonde for the reasons well expressed by the referee.

The new sentence is: "Second, the measurements are all averaged over 15 minutes starting at the launch time of RAOB".

I miss information about bandwidths, system noise temperatures, and integration times for the different radiometer channels? Since the radiometers are main instruments in the comparisons I think such information shall be in the paper rather than just a reference to an older paper.

We have added the information at the beginning of section 2.1. Both radiometers have bandwidth of 300 MHz for the 23.8 and 30 GHz and 1900 MHz for the 90 GHz. The system noise temperature is < 500 K for the K-band channels and < 1100 K for the W-band channel and the integration time is 1 s for all channels.

I am confused by the description of the retrieval uncertainty for the MWR. First you say that it is expected to be 0.5 kg/m² and with the addition of the high frequency channel it can be reduced to 0.4 kg/m² (page 4, lines 8-9). Thereafter, (same page line 20) you say that the best retrieval algorithm resulted in an SD of 0.72 kg/m². I must have missed a crucial point, please explain.

The quoted uncertainty in the retrieval (0.5 kg/m² for a two-channel and 0.4 kg/m² for a 3-channel retrieval) is an estimated theoretical uncertainty derived by accounting for the calibration uncertainty combined with the sensitivity of each channel to water vapour (intended as the slope of TB vs PWV, see for example Racette et al., 2005, now added in the reference list). Assuming a calibration uncertainty of 0.3 K for the K-band channels (23.8 and 31 GHz) and 0.5 K for the W-band channel (89 GHz) the uncertainty in the water vapour can be derived as DPWV=DTb/slope. Because we are in the linear regime of the sensitivity we can follow Racette et. al. for the estimated slopes (1.25, 0.34,

and 1.8 K/mm) and estimate the uncertainty of PWV derived from each single channel as 0.24, 0.88, and 0.28 kg/m². [Racette et al., Measurement of Low Amounts of Precipitable Water Vapor Using Ground-Based Millimeter wave Radiometry, J. Atmos. Oceanic. Techn., 22, 5, 317-337, 2005]. We added text in section 2.1 to explain this.

The SD=0.72 kg/m² refers to the minimum IWV SD produced by the “best” selected retrieval algorithm derived from a statistical dataset of radiosonde from the Jyväskylä station. The retrieval algorithm consisting of a set of retrieval coefficients of a polynomial equation able to predict IWV from MWR observations was derived from a simulated training dataset, that includes clear-sky and cloudy conditions, and its performance is evaluated by applying it to a simulated independent test dataset.

The total uncertainty of the retrieval will depend on:

- intrinsic variability of the used dataset;
- how well the dataset represents the climate of the region under analysis;
- RTE used to derive simulation also including a cloud model;
- predictors;
- polynomial expressions.

You mention the dry bias correction when describing the RAOB data, but it is unclear if you applied any correction, and if so which one?

We used the radiosondes sounding provided by the ARM archives (www.arm.gov). The radiosondes are RS92 and are processed using the standard Vaisala processing. No additional correction was applied to the radiosondes. We added text (Subsection 2.1) to better explain this point.

You present a short data segment from March 26, 2014, in Figure 2. Why did you select this specific period? Is it a typical period, or perhaps a period that is very stable (with low variability)?

Yes, the selected segment was a clear-sky night time segment with low vapour variability. We added more explanation in section 3 to explain this better.

You say that the different height of the GPS site was accounted for (page 7), but you do not explain how

This sentence, as well as a similar sentence on page 4 were actually left over from a previous version of the manuscript where we had used radiosondes from the station of Sodankylä which is at a higher elevation. In the current form the radiosondes from the station of Jyväskylä were used, to avoid any correction term. We thank the reviewer for this comment that prompted us to review the site locations and verify our calculations. The elevation of the instrumental 3 sites (Orivesi for GPS, Hyytiälä for MWRs & BAECC profiles, and Jyväskylä for the long-term RAOBs) were double checked using NASA/ASTER Digital Elevation Model data that has an estimated accuracy of ~ 15 m, and were found to agree in within 10 meters. Therefore, no corrections were applied. The sentences were removed.

Technical Corrections

page 1, line 13: In this work, we examine → We examine -Done

page 1, line 26 (and many other places): there shall be a space between the value and the unit (also the % unit) according to SI rules. -Done, thank you

page 3: you may want to mention that the 89 GHz frequency is not only more sensitive to water vapour, but also to liquid water (clouds) which is a potential problem. This text could perhaps make more sense in Subsection 2.1 where the MWR is described.

Thank you we added a mention of this. The liquid water is accounted for when the retrievals are derived by simulating clouds in the column.

page 3, end of introduction: it is common practise to refer to the section numbers when the structure of the papers is presented. It is helpful for the reader.

We modified the last paragraph of Section 1 to provide a short overview of the sections of the paper.

page 3: A better title for Subsection 2.1 could be "Microwave radiometers and radiosondes" ? It will match the title of Subsection 2.2. -Done

page 4, line 30: the lunch times seem strange? I expect 6 h between the launches?

The 00 hours is actually 23. The time of the sonde launch generally varies between 15 and 35 minutes after the hour. For example, on 04/09/2014 the actual sonde launch was at 5:30, 11:16, 17:19, 23:20, however the exact time of the launch varies daily. We changed 00 to 23.

page 5, line 17: in zenith delay → in the zenith delay - Done

page 7, line 29: low differences → low mean differences? smallest differences → smallest mean differences? -Changed

page 8, line 7: Differences → Mean differences - Changed

page 8, line 10: representativeness errors due to → the true differences caused by

We changed this to “differences in the observed air masses caused by”

page 9, line 22: one RAOB → RAOBs? -Done

Figure 1: I suggest to remove the text from the picture frame and describe which instruments (from left to right) that are seen in the figure caption. You may also want to mention the third instrument, the one to the right?

Done, we have removed text and added information in the caption

Figure 3: It is very difficult to see more than one of the time series. An alternative would be to show only one time series for the IWV and present the others as differences from this one in individual subgraphs below.

This is a very good suggestion. We followed the reviewer's suggestion and left the GPS time series in the top panel. In the bottom panel we show the differences between GPS and the other instruments. This shows the increased variability during the months of June and July probably due to increased cloudiness and variability of the water vapor. In the new version of the manuscript, Figure 3 → Figure 4.

Figure 4: I would prefer to have the important quantitative information either in the figure caption or in a separate table, if you regard it as important.

Done. Following both reviewers' suggestions added Table 3 that contains the quantitative information. In the new version of the manuscript, the Figure4 -> Figure 5.

Figure 7: Some of the red squares are hard to see. Plot them with larger symbols and perhaps a more light red colour. And since they are few, plot them on top of the black circles.

Done, they were already on top, but because of the color they were not visible. In the new version of the manuscript, Figure 7 -> Figure 8.

Figure 8: Mean and standard deviation of the measurement of each instrument → RMS differences for each instrument pair vs the mean IWV.

The right side of Fig. 8 was not correct. We re-plotted it. It represents the standard deviation of the water vapor in the FOV of each instrument in each water vapor bin. In the new version of the manuscript, Figure 8 -> Figure 9.